Paper 1, Poster 1

THE APL TIME AND FREQUENCY LABORATORY

Richard Dragonette and Mihran Miranian
Johns Hopkins University Applied Physics Laboratory

ABSTRACT

The APL Time and Frequency Lab (TFL) supports a wide variety of current and up-coming NASA missions that range from the study of the Earth's upper atmosphere to the examination of the planet Pluto and the Kuiper belt. This support can be in the form of providing precise time and frequency to the integration and testing of new hardware or the time stamping of ground-receipt telemetry packets from various spacecraft. The laboratory's ensemble of three Agilent 5071A cæsium standards and one hydrogen maser will soon be enlarged with the procurement of two additional Datum hydrogen masers. Also, a new Timing Solutions measurement system is capable of making up to once-per- second picosecond level phase measurements at 5 MHz of each clock in the ensemble. Traceability to the USNO, NIST, and the BIPM is maintained via GPS common-view time transfer and will provide a means for incorporating the laboratory's clocks into the computation of TAI.

Paper 2, Poster 2

TIME AND FREQUENCY ACTIVITIES AT THE CSIR NATIONAL METROLOGY LABORATORY

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National Metrology Laboratory, South Africa

ABSTRACT

The CSIR - National Metrology Laboratory (CSIR-NML) is the custodian of the South African national measurement standards. The Time and Frequency (TF) laboratory is responsible for the maintenance of the SI second, which is the most accurate standard currently maintained. In addition to maintaining the national timescale, the TF laboratory is also responsible for a number of other parameters, including fast electrical pulse characterization, phase angle and a number of fibre optic parameters. A project in which the TF laboratory is taking a leading role is currently under way to look into the feasibility of establishing a femtosecond comb at the CSIR-NML. The current status of this project will be reported at the meeting.

Paper 3, Poster 3

TIME AND FREQUENCY ACTIVITIES AT THE U.S. NAVAL OBSERVATORY

Demetrios Matsakis
U.S. Naval Observatory

Abstract

The U.S. Naval Observatory (USNO) serves as the timing reference for the U.S. Department of Defense, and maintains over 70 high-performance cesium clocks and 18 cavity-tuned masers. Almost every aspect of timekeeping at the USNO is being upgraded, with a view to providing a better timing reference for our users. Improvements in frequency standards, timescale algorithms, clock steering, and time-transfer will be discussed.

Paper 4, Poster 4

METAS TIME AND FREQUENCY LABORATORY ACTIVITIES IN 2003

Laurent-Guy Bernier, Gregor Dudle, and Christian Schlunegger
Swiss Federal Office of METrology and Accreditation, Switzerland

Abstract

METAS is the Swiss federal office of METrology and Accreditation. The METAS Time and Frequency Laboratory (TFL) is responsible for the generation and dissemination of precise time in Switzerland and performs calibrations for customers. The TFL staff also provides technical expertise to the SAS, the Swiss Accreditation Service.

The TFL operates a small ensemble of commercial cesium clocks used to generate the UTC(CH) and TA(CH) national timescales. The cesium clocks also contribute to the generation of TAI and UTC. A conventional C/A code GPS common view link is operated for the time transfer to the BIPM of the TAI contributing clocks. The TFL also operates the HBG VLF 75 kHz time signal transmitter, as well as a public NTP server and a telephone/modem remote time service.

After many years of development, a continuous beam cold cesium atom fountain is now ready to be put into active service as a primary frequency standard. The cesium fountain was developed in collaboration with the Observatoire de Neuchâtel. A hydrogen maser was also acquired in 2003. It will be used as a reference frequency standard for the evaluation of the fountain and for the generation of a local real time realization of UTC.

A TWSTFT link is in the design and planning stage. A P3 link was set up as part of the TAIP3 experimental network organized by the BIPM. The P3 link is a GPS common view link based on the Ashtec Z12T geodetic time receiver. It is expected to provide significantly better performance than the conventional common view technique based on single channel C/A code GPS time receivers.

Paper 5, Poster 5

NATIONAL TIME AND FREQUENCY SERVICE OF THE RUSSIAN FEDERATION

V. Krutikov, Gosstandard of Russia
V. Kostromin and N.Koshelyaevsky,
Institute of Metrology for Time and Space, Russia

Abstract

The National Time and Frequency Service (NTFS) of Russian Federation (RF) was established in 1947 in accordance with a decree of USSR Government.

NTFS realizes scientific, technical and metrology activity in the keeping of UTC(SU) – the national time scale of the Russian Federation, determination of the Earth Orientation Parameters (EOP), ensuring national needs in time standard signals, providing in that way the unification of time and frequency measurements and EOP determination in the Russian Federation.

The technical means for unification of time and frequency measurements and EOP in Russia are: state time and frequency standard (STFS) and system of secondary time laboratories (STL); time standard signals emitting stations; astro-optical, radiointerferometrical and monitoring stations of the space and geodetical systems.

All these activities are realized under the scientific, methodical and operational auspices of the Main Metrological Center of NTFS which is located in the Institute of Metrology for Time and Space GP (VNIIFTRI). The information from NTFS regarding time, frequency and EOP is obligatory in Russia.

The most substantial performances of NTFS are determined by STFS. The mean UTC(SU) time unit difference relative to the SI second in 2002 was less then 0.2×10^{-14} . The time unit keeping, atomic, TA(SU), and coordinated, UTC(SU), time scales generation is based on the ensemble of hydrogen masers. Time scale TA(SU) relative instability is $\sigma_y(\tau) \approx 1 \times 10^{-15} (1 \leq 20 \text{ days})$ and the UTC(SU) time scale difference relative to UTC do not exceeded 100 ns.

The time units differences supported by STL located in Mendeleevo, Novosibirsk, Irkutsk and Khabarovsk are within 2×10^{-14} to 4×10^{-14}, time scale instabilities of TA(STL) $\sigma_y(\tau) \leq 1 \times 10^{-14}$ $(10 \leq \tau \leq 100 \text{ days})$ and $|$UTC(SU)-UTC(STL)$| \leq 100$ ns.

Taking into account qualified personnel, high performances and very advantageous geographical location today we apply knowledge and infrastructure of NTFS laboratories as GLONASS monitoring stations, as base station of state network of differential satellite navigation system and other applications wanted precise time and coordinates support.

Paper 6, Poster 6

LITHUANIAN NATIONAL TIME AND FREQUENCY STANDARD

Rimantas Miškinis
Semiconductor Physics Institute, Lithuania

Abstract

The Lithuanian National Time and Frequency Standard Laboratory is responsible for the maintenance and dissemination of the national time scale UTC(LT), time and frequency units. Since June 2001, the Lithuanian Time and Frequency Standard has been contributing to TAI. The laboratory is equipped with two HP 5071A cesium atomic clocks (one with a high performance Cs tube) and two multi-channel GPS receivers TTS-2 based on Motorola VP Oncore GPS processors. One of the GPS receivers is equipped with a temperature stabilized GPS antenna. For the dissemination of the Lithuanian Time Scale UTC(LT), the NTP server Datum 2001 is used. In this paper, the main metrological characteristics and technical possibilities of the Lithuanian Time and Frequency Standard are presented.

Paper 7, Poster 7

INITIAL TESTING OF A NEW GPS RECEIVER, THE POLARX2, FOR TIME AND FREQUENCY TRANSFER USING DUAL FREQUENCY CODES AND CARRIER PHASE

Pascale Defraigne, Carine Bruyninx, and Fabian Roosbeek
Royal Observatory of Belgium, Belgium

Abstract

To contribute to the TAI, the Royal Observatory of Belgium (ORB) routinely performs all-in-view time transfer based on an Ashtech Z-XII3T GPS receiver and using the RINEX-CGGTTS conversion software developed in-house. The Ashtech Z-XII3T is steered by an active H-maser CH1-75, which is used to generate the local realization of UTC, UTC(ORB). The receiver participates in the BIPM pilot project TAIP3 (TAI time links with geodetic receivers using the ionospheric free combination P3), and its data are used by the International GPS Service (IGS); the H-maser is consequently also included in the IGS time scale. The production of the Ashtech Z-XII3 (the core of the Ashtech Z-XII3T) ended some time ago and repair services will only be available for the Z-XII for as long as replacement parts are available, with end-of-life estimated to occur in October 2004. In order to anticipate the renewal of its time transfer equipment, the ORB has started to test a new geodetic GPS receiver, the POLARX2, also suitable for time transfer applications. The receiver was developed by Septentrio, located in Belgium. The paper will describe the initial tests performed with the POLARX2. It will evaluate the potential of this receiver for both time transfer based on code data, and frequency transfer based on carrier phases analyses.

Paper 8, Poster 8

TIME AND FREQUENCY ACTIVITIES AT THE NATIONAL PHYSICAL LABORATORY

J. A. Davis, P. B. Whibberley, R. Hlavac and P. W. Stacey
National Physical Laboratory, United Kingdom

Abstract

The National Physical Laboratory (NPL) is the national metrology laboratory for the U.K. NPL maintains the U.K. national time scale UTC(NPL), disseminates time and frequency in the UK and beyond, undertakes time and frequency research and acts as a focus for time and frequency related issues.

NPL's national time scale UTC(NPL) is based on an ensemble of three active hydrogen masers and three cæsium clocks. A composite time scale based on a modern Kalman filter based combining algorithm is being developed. This work will improve NPL's ability to predict future values of UTC-UTC(NPL) and estimate the uncertainty in these measurements. A cæsium fountain primary frequency standard is operated routinely and its frequency shifts have been evaluated. The fountain standard will both contribute to TAI and improve significantly the performance of UTC(NPL).

NPL operates a wide range of satellite time transfer methods, including GPS common-view, geodetic GPS time transfer using NPL's IGS station, and two-way time transfer using geostationary telecommunications satellites. Analysis methods are being developed to combine measurements obtained from these different techniques in an optimal way.

NPL provides a range of services to disseminate time and frequency within the U.K. A GPS common-view time and frequency transfer service is available to users anywhere in the UK who require the continuous monitoring of frequency standards at the highest accuracy. NPL also offers a characterization service for atomic frequency standards and GPS disciplined oscillators. The MSF 60 kHz time and frequency signal controlled by NPL is widely used within the U.K. by both businesses and the general public, while the NPL Telephone Time Service provides the means to synchronize PCs via a modem connection.

Paper 9, Poster 9

AN UPDATE ON PTB'S ACTIVITIES IN TIME AND FREQUENCY

D. Piester, A. Bauch, J. Becker, and T. Polewka
Physikalisch-Technische Bundesanstalt, Germany

Abstract

Recent activities in the field of time and frequency metrology pursued at PTB are reviewed.

Operation of the cæsium fountain frequency standard CSF1 has been continued during more than 95% of the total possible operation time. We will report on the results of comparisons with other fountains and with local frequency references.

The realization of UTC(PTB) was upgraded during 2003 with the aim of a time scale being stable in the short term and the long term. This time scale also serves as the time reference in the Orbit Determination and Time Synchronization process in the Galileo Testbed V1 which is pursued under contract with Alenia Spazio, Torino. PTB also serves as the UTC(k) laboratory involved in steering the experimental Galileo system time to TAI.

In co-operation with BIPM and timing institutes in the U.S. and Europe several calibration exercises have been conducted which resulted in an improved calibration of PTB's time comparison equipment.

These three topics will be subject of detailed presentations during the conference.

Paper 10

THE FIRST TWO-WAY TIME TRANSFER LINK BETWEEN ASIA AND EUROPE

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Chungwha Telecom Company, Taiwan
G. de Jong, E. Kroon, and M. J. Brakel
NMi, Van Swinden Laboratories, The Netherlands

Abstract

The Two-Way Satellite Time and Frequency Transfer (TWSTFT) experiment performed between TL (Taiwan) and VSL (the Netherlands) is herewith reported. The feasibility of the TWSTFT link between the European and Asian laboratories was first demonstrated.

TWSTFT is one of the major time-transfer techniques because of the high precision that can be achieved. The time-transfer data obtained from the regular experiments in European and North American have been used to calculate the international atomic time (TAI). The development of TWSTFT in Asia-Pacific Rim region has also been active recently. Three links, including CRL/NMIJ, CRL/NTSC and CRL/TL, have been introduced into the computation of TAI since January 2002. However, the only time transfer link currently existing between Europe and Asia is the PTB-CRL GPS CV single channel link. A real Asia-Europe TWSTFT link would be very helpful to enhance the time transfer reliability and be beneficial to the TAI contributions from the Asia-Pacific region.

The topic of establishing an Asia-Europe link was first discussed in the 9th TWSTFT meeting of the CCTF WG. Both TL and VSL are interested in setting up this link. After several satellites were surveyed, the PAS-4 satellite at 72°E was found to be suitable for the TL-VSL link.

Both TL and VSL were devoted to the establishment of the TL-VSL link. The pretest was performed successfully on February 19, 2003. The follow-on tests also showed that the performance of the TL-VSL link was good. Therefore, the regular experiment has been discussed and undertaken from the middle of March 2003. The development, results and conclusions about this link are illustrated in this report.

Although the elevation from VSL was only 4.9 degrees, the performance of this link is still good. The TWSTFT results are compared with those of the GPS CV method in this report. The RMS value of the difference between these two methods is less than 3.0 ns. By establishing the TL-VSL link, the feasibility of using the TWSTFT method for routine comparison between Asia and Europe has been demonstrated.

Paper 11

A NEW MULTI–SYSTEM TIME RECEIVER

J. Nawrocki and P. Nogas
Polish Academy of Sciences, Poland

Abstract

There are now available four types of navigation satellites suitable for time and frequency transfer: GPS, GLONASS, WAAS and EGNOS. This paper describes a new time-transfer system TTS-3, based on a Javad Legacy receiver, allowing observations of these satellites simultaneously in multi- channel and multi-frequency mode. The following codes are used: C/A-code for GPS, WAAS, EGNOS and GLONASS, P-code for GLONASS and reconstructed P-code for GPS. Hardware of the receiver, treatment of observations, and output data fulfil the recommendations of the CCTF Group on GNSS Time Transfer Standards (CGGTTS). The structure of the new time-transfer unit is described in brief, and the results of some multi-system time-transfer tests are presented.

Paper 12

COMMON VIEW LORAN-C FOR PRECISION TIME RECOVERY

LT Kevin Carroll, U.S. Coast Guard
Tom Celano and Casey Biggs, Timing Solutions Corporation
Mike Lombardi, National Institute od Standards and Technology

Abstract

The LORAN-C network is being recapitalized to serve as a backup to GPS for navigation and timing. LORAN-C is being investigated as a precision (sub 100 ns) time recovery system for use in CONUS. Traditionally, LORAN-C time recovery has been limited by propagation effects (both spatial and temporal) to provide time recovery in the microsecond range. By employing common view techniques long used in GPS, the potential exists to enhance LORAN-C time recovery performance by over an order of magnitude. The LORAN-C Accuracy Panel (run by the U.S. Coast Guard) has sponsored a research project to collect data and determine the expected performance level for time recovery using common-view LORAN-C. This paper presents the results of that work.

This paper begins with a short overview of the LORAN-C recapitalization project with an emphasis on timing enhancements at the transmitting stations. A description of the common-view LORAN-C test network follows. Data collected in Boulder will be corrected via common-view using a near field station and a far field station. Results will be analyzed to determine the dependence of time recovery precision on distance. The common view data will be analyzed for long term effects and stability. The data will be used to construct a noise model which will then be implemented in an existing clock simulator to demonstrate clock performance with LORAN-C when GPS is not available.

Paper 13

TIME TRANSFER BETWEEN USNO AND PTB: OPERATION AND CALIBRATION RESULTS

D. Piester, A. Bauch, J. Becker, and T. H. Polewka
Physikalisch-Technische Bundesanstalt, Germany

D. Matsakis and A. McKinley
U.S. Naval Observatory

Abstract

Two-way satellite time and frequency transfer (TWSTFT) is routinely executed between USNO and PTB via two links, Ku-band and X-band, respectively. While Ku-band measurements are performed 5 times per week (together with several European and American time laboratories), X-band measurements are carried out nominally 24 times per day. By this means H-masers of both laboratories are compared during 15 minutes each hour. Since June 2003 the results are evaluated by the BIPM for a future involvement in the production of TAI. Thus a periodical calibration of the link is strongly desirable. Up to now three calibration experiments have been carried out by a transportable TWSTFT station from USNO: in June 2002, January 2003, and July 2003. Because only a few TWSTFT calibrations of civil time laboratories have been performed up to now, this first semiannual schedule provide the opportunity to characterize the instability of the TW links e.g. related to environmental factors. In this contribution the experiments and its results will be discussed.

Beside the X-band, TWSTFT USNO and PTB compare their clocks also with Ku-band TWSTFT (see above) and GPS common view. Furthermore both stations are participating in the TAIP3 experiment by means of geodetic GPS receivers. The performance of TW and GPS links will be discussed.

Paper 14

MCS ZERO AGE OF DATA MEASUREMENT TECHNIQUES

Gary L. Dieter, Gregory E. Hatten, Jack Taylor
Boeing Homeland Security and Services

Abstract

Advances in 1999 provided Boeing GPS navigation payload analysts the ability to transfer, archive, and manipulate Master Control Station (MCS) Kalman filter data. Since then, this data has been reported in the System Performance Measurement and Analysis (SPMA) quarterly report, and used to assess GPS performance through a variety of metrics, including Zero Age of Data error. This error, a byproduct of the real-time, predictive nature of the MCS Kalman filter, affects many navigation and time-transfer users.

This paper describes the methodology by which the MCS Kalman filter states are compared to "truth" sources such as NIMA and IGS to calculate Zero Age of Data error. Results show that typical Zero Age of Data errors vary from spacecraft to spacecraft and over time. Also examined are on-orbit frequency standard, ephemeris, and solar events and their associated impacts on Zero Age of Data error. Future efforts to improve Zero Age of Data error are explored. Conclusions reveal that considerable insight is gained by calculating and observing Zero Age of Data characteristics in the effort to understand and reduce this error source in the future.

Paper 15

GPS IR RUBIDIUM CLOCKS: IN-ORBIT PERFORMANCE ASPECTS

Marvin Epstein, Gerald L. Freed, and John Rajan
ITT Industries

Abstract

The GPS Block IIR Rubidium clocks have proven to be the best performers in the current GPS constellation starting with the first IIR operational clock (launched on July 23, 1997). This discussion covers a number of topics including the frequency accuracy of the clocks, the frequency variation and the projected lifetimes of these clocks. The performance of these clocks in orbit and their life expectancy are compared with that experienced with previous GPS clocks. The superior performance and lifetimes of the GPS IIR Rb clocks are highlighted. Because these clocks are so well behaved, it has been possible to detect various features and phenomena that were not previously detectable. The diagnostic and re-programmability capability of the GPS IIR Satellites allows these discrepancies to be addressed. The full drift of the IIR clocks is not observed by the user because of on-board cancellation by the Time Keeping System. The long lived features of the clocks indicate that they will outlive the GPS satellite mission duration.

Paper 16

UNCERTAINTY ESTIMATION ON GPS TIME TRANSFER

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Observatoire de Besançon, France

Abstract

The traditional GPS common view technique, using C/A code receivers, is the main time transfer method used by various timing laboratories over the word. Moreover, this method is used to realize the TAI (Temps Atomique International) and the TA(F) (Temps Atomique Français). Clock offsets between laboratory clocks are determined according to a fixed procedure imposed by the CCTF (Comité Consultatif du Temps et des Fréquences). Using this procedure, one can perform on average 54 tracks per day (theoretically 90 tracks per day) providing with clock offsets. Each of these clock offsets is obtained as the result of a quadratic regression, followed by various model based corrections and finally a linear regression. The clock offsets are then issued with their standard deviations. However, it is a simplified estimate that does not take into account the statistical properties of the different types of noise. We propose here to rigorously estimate this time uncertainty for various types of noise which characterize the transmitted GPS time offset data. This is achieved by the calculation of the covariance matrix of time samples. This method provides us with the variances of drift coefficients and of the residuals, in the case of a linear drift model for one-day sample sets, taking account of the different types of noise. We compare in this paper the obtained results with simulated and real data over several days.

Paper 17

GPS CLOCK/TIMESCALE MANAGEMENT IN THE MASTER CONTROL STATION

Steven Hutsell, Schreiver Air Force Base
Gary Dieter and Greg Hatten, Boeing
Theodore Dass and Jeff Harvey, ITT

Abstract

Master Control Station (MCS) operators are responsible for managing several clocks and timescales embedded within the Global Positioning System (GPS). These timescales include satellite time, monitor station time, GPS time, and GPS's prediction of UTC(USNO). MCS software provides several utilities for performing clock/timescale management. Because of the apparent commonalities between the various clocks/timescales, many often confuse the various activities the 2d Space Operations Squadron (2 SOPS) performs to adjust, tune, steer, and otherwise control these clocks/timescales. This paper concisely details many of these activities, to clarify the distinctions between the various clock/timescale management functions.

Paper 18

REAL-TIME TIME AND FREQUENCY TRANSFER USING GPS CARRIER PHASE OBSERVATIONS

Carsten Rieck, Per Jarlemark, Kenneth Jaldehag, and Jan Johansson
Swedish National Testing and Research Institute, Sweden

Abstract

This paper focuses on real-time differential time transfer in comparison with post processing solutions. Today, it is possible to obtain a precision in the time difference estimates in the order of several tens of picoseconds at best. As with all phase based solutions it is difficult to achieve a reasonable absolute value without special time receivers available. Thus results are presented with an arbitrary offset removed and only the precision of the methods are studied in this paper.

During earlier investigations several different real time methods were developed and initially performance tested. The methods could be distinguished by how and if satellite parameters were estimated and whether differences was used or not. Even though the first measurements lacked reliable statistics, the differential approach using predicted satellite orbits and clocks, showed very promising results and was therefore chosen to be used for a more permanent setup. Favoring local networks, the method uses station pair wise common view observations for estimating the station and atmospheric parameters. A stable and permanent real time network was established that includes SWEPOS/IGS stations at Onsala and Borås, and a third SWEPOS location in Stockholm. All these stations have several atomic frequency standards of CS or hydrogen maser type feeding one or several receivers connected to a Dorme-Magolin type antenna in zero base line. All used frequency standards are continuously measured against UTC(SP) using GPS code common view and are as well reported to the BIPM. Improvements were also made to the Kalman filter based software, its experimental code was ported into a POSIX environment and completed with communication and management tools that allow easy extension of the network and data handling. The mean for comparing the the data was the postprocessing geodetic GIPSY/OASIS. In order to provide independent data also a set of local time interval measurements were used.

As a result, the measurements confirm the ability of the described method to provide differential time estimates in the sub-ns range. The rms difference between the real time carrier phase based and the post processed estimates of the station time differences are at a level of 50 picoseconds with an arbitrary offset subtracted.

Paper 19

PERFORMANCE SUMMARY OF GPS TIMING SIGNALS

Jay Oaks, Ken Senior, and Marie M. Largay,
U.S. Naval Research Laboratory
Wilson G. Reid, SFA, Incorporated
James A. Buisson, AEI, Incorporated

Abstract

The Naval Research Laboratory (NRL) conducts comprehensive analyses of the Global Positioning System (GPS) atomic frequency standards under the sponsorship of the GPS Joint Program Office (JPO) and in cooperation with the 2nd Space Operations Squadron (2 SOPS) at the Master Control Station (MCS) in Colorado Springs, Colorado. The purpose of the analyses is to determine the performance of the timing signals originating with the atomic frequency standards carried aboard the space vehicles. Metrics used in the analyses and presented in this paper include frequency, drift, and stability histories and stability profiles based on the Allan and Hadamard variances. Also presented in this paper are comparisons of performance based on the broadcast as well as the precise post-fit ephemerides.

Paper 20

GALILEO TIME DISSEMINATION AND COMMON VIEW: HOW ACCURATE WILL IT BE?

A. Moudrak and J. Furthner
German Aerospace Center (DLR), Germany

Abstract

Future European navigation system Galileo will provide both positioning and timing capabilities to its users in the frame of four basic services: Open Service (OS), Safety-of-Life Service (SOL), Commercial Service and Public Regulated Service. SOL will provide the highest performance among these four services which will be also guaranteed. Therefore, SOL seems to be a good candidate for critical timing applications like telecommunications. It might be also used to link timing labs contributing to UTC/TAI. However timing performance of SOL is currently not specified in Galileo programmatic documents available for public use. Our paper is dedicated to the investigation of timing accuracy provided (and implicitly guaranteed!) to SOL users in stand-alone and differential (Common View) modes.

In the first section of the paper we present transformation of Galileo SOL positioning performance into timing performance for stand-alone static and dynamic users. The transformation is based on global simulations of Galileo geometry made with DLR's GNSS simulator NavSim© , which also allowed one to produce global maps of Galileo timing accuracy. Similar maps for GPS and combination of GPS and Galileo are also shown in the paper.

Metrological time keeping requires one to estimate time and frequency offsets between clocks of remote time labs. A conventional method for this application is Common View of GPS satellites. This method can be implemented in future also with Galileo.

Accuracy of Common View strongly depends on the de-correlation of ephemeris errors and residual propagation effect and decreases with distance. To assess the accuracy of Galileo and combined Galileo/GPS Common View we have simulated Galileo and GPS observations for various distances between time labs. The simulated observations were processed with the software available in the frame of BIPM TAIP3 Pilot Project which produces Common View data in BIPM data exchange format. Results of the simulations and data processing allowed us to evaluate the accuracy of Galileo and combined Galileo/GPS Common View time transfer.

Paper 21

GPS AND GALILEO: USER ISSUES, CONCERNS, AND EXPECTATIONS FOR OPERATING IN A MULTI-SYSTEM GNSS

Rosalind Lewis, Elham Ghasghai, Gordon Bitko and Michael Kennedy
The RAND Corporation

Abstract

In the not too distant future there may be a second global space-based positioning, navigation, and timing (PNT) capability similar to the Global Positioning System (GPS). The EU plans to begin initial operations of the Galileo PNT system in 2008. The impact to global economic and security conditions, as a result of this additional highly capable information utility, is uncertain. Policy leaders and technical experts have been in discussion since 2000 to find cooperative means of providing users the benefit of both systems. This paper summarizes industry surveys that were collected in support of a study to explore the economic impact of Galileo on GPS as a result of competition. In that study three factors informed the considerations of competition: interoperability and compatibility; strategies employed to foster Galileo adoption; and the GPS modernization and Galileo development. What influence might these factors have on the user response to GPS and Galileo in a future where both systems co-exist?

In performing our research we developed an instrument to characterize and postulate the user response (market demand) for space-based PNT as a function of these competitive factors. The instrument was widely distributed to companies (as proxy for the user) operating in various market segments such as consumer, survey, transportation and equipment manufacturing. It included questions related to performance, management, and utilization of space-based PNT information. The responses we received are suggestive of what users want and expect from a multi-system GNSS. Specifically respondents answered questions such as, what performance parameters are critical and what sort of improvement in performance is needed? What are your future plans for use of space-based PNT data? What are your concerns and expectations for operating in a global, multi-system GNSS?

Paper 22

APPLICATION OF THE GSF-1 ALGORITHM TO THE NEAR-OPTIMAL TIMESCALE PREDICTION OF THE HYDROGEN MASER

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METAS, Switzerland

Abstract

The GSF-1 timescale predictor is defined as: $x(t+\tau_1) = x(t) + \tau_1 y(t_1, \tau_2) + \epsilon(t, \tau_1, \tau_2)$, where $x(t)$ is the present value, $x(t+\tau_1)$ is the future value, and $\epsilon(t, \tau_1, \tau_2)$ the error on the prediction. The GSF-1 predictor is simply the initial value, $x(t)$ plus the initial average frequency offset $y(t, \tau_1) = \frac{x(t)-x(t-\tau_2)}{\tau_2}$ multiplied by the prediction interval, τ_1.

The RMS prediction error can be minimized for a given prediction interval, τ_1, by optimizing the averaging interval, τ_2. It can be verified that the rms error of the optimized GSF-1 predictor The paper proposes a simple is close to the true optimum, in the sense of optimal linear prediction, when appled to a timescale affected by a combination of white frequency noise and flicker frequency noise, such as the timescale from a cesium clock.

The timescale from a hydrogen maser, on the other hand, is affected not only by white frequency noise and flicker frequency noise, but also by a deterministic drift of the frequency. The paper proposes a simple generalization of the GSF-1 predictor with two parameters:the averaging interval, τ_2, and the drift coefficient, d. It is shown that, after optimization of both parameters, the rms error comes close to the true optimum also in the case of the hydrogen maser. The algorithm is validated using actual hydrogen maser timescale data published by the BIPM. In the typical case of the hydrogen maser with a frequency drift of $1 \times 10^{-16}/\mathrm{d}$ and a residual flicker floor of $[1.5, 2.0] \times 10^{-15}$, an rms prediction error of 12 ns can be obtained for a prediction interval of 60 d. We plan to use this simple prediction algorithm as an aid for the steering to UTC, via Circular T, of our new hydrogen maser.

The paper also uses a simple method to determine the rms error of the optimal linear predictor, i.e., the true optimum, associated with any particular combination of independent elementary noise processes (white FM, flicker FM, etc.), without a knowledge of the optimal linear predictor itself. This method makes possible the rating of practical predictor by defining its optimality ratio, i.e., the ratio between its actual rms error and the true optimum.

Paper 23

MTIE AND TDEV ANALYSIS OF UNEVENLY SPACED TIME SERIES DATA AND ITS APPLICATION TO TELECOMMUNICATIONS SYNCHRONIZATION MEASUREMENTS

Mingfu Li, Chia-Shu Liao
Chunhwa Telecom, Taiwan

Abstract

MTIE and TDEV are key parameters for network synchronization measurement. According to the MTIE and TDEV definitions, the samples are assumed to be evenly spaced. However, all the samples are often not separated evenly, due to the instrumental errors, noise interference or data loss. In such a case, is the MTIE or TDEV computation is still correct or reliable? In this work, we investigated the effect of uneven data spacing on the computations of MTIE and TDEV. We evaluated MTIE and TDEV with unevenly spaced data having the five different power-law noise types. Each simulated data set had 3600 evenly spaced data points spaced one second apart. In the next step, we removed data points for each file according to the parameter p. Each data point in a file will be removed with probability p and not removed with probability. And for the unevenly spaced data files, the averaging spacing was recomputed. Then we computed MTIE and TDEV for these data files with different p values. The results show that when p is larger, the error compared to the case with (evenly spaced data) is also larger. However, the difference is not significant. Therefore, we conclude that the difference between the computation results of evenly and unevenly spaced data files is not significant. It reveals that we can ignore the effect of unevenly spaced data for MTIE and TDEV computations. Based on the results, one can employ a simple model to conduct the network synchronization measurement. In other words, in the telecommunication synchronization measurement, a clock recovery device that recovers the timing signal from the data bits is no more required. We can input the network data signal to the time interval counter (TIC) directly. The measured data is often not evenly spaced since the data bits of "1" and "0" are not distributed regularly. But based on the previous results, this novel measurement model can still be validated.

Paper 24

THE TRADE-OFF OF SPACE STATE AND FIR FILTERING ALGORITHMS IN GPS-BASED OPTIMAL CONTROL OF A LOCAL CLOCK

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Abstract

Fast and accurate synchronization of a local clock along with accurate estimation of the clock performance (time error, frequency offset, and aging) still remains a key problem in GPS-based timekeeping. Basically, it is solved employing the linear estimation theory (linear Kalman filtering) via the recursive space state (1-3 state) time scale algorithms and finite impulse response (FIR) filters based on the simple (equal constant coefficients), linear, or exponential (low pass) moving average (MA) model of the clock. In our previous reports (for FIR filters), we have shown that no one of the above listed estimation algorithms is universal for timekeeping in terms of minimum produced errors. The problem is primarily in the clock model, which is traditionally limited by three states, among which the third state (it is assumed to be aging) cannot usually be estimated for the filter memory. Furthermore, the assumed noise is not actually stationary Gaussian owing to environment (temperature, for the first hand). Respectively, different filtering algorithms of the same time constant provide for with different estimation and control errors. In this report, we numerically investigate the trade-off between the space state algorithms (Kalman filtering) and FIR filtering algorithms intended to provide optimal time error steering of the local crystal clock employing the GPS reference time signals. We employ four filters, namely 1) 2-state Kalman, 2) 3-state Kalman, 3) FIR with the constant kernel (simple MA), and 4) FIR with the linear kernel (optimally unbiased MA). The control problem is optimally solved for the GPS-based time error database measured for the crystal clock. We study the discrete time control system of a local clock assuming the latter to be ideal (linear) and inertialess with respect to the filter memory. Based upon a separation principle, we numerically determine the optimal control coefficients for each of the filtering algorithms. We finally bring a numerical evidence for the estimation and control errors provided with all four exploited algorithms.

Paper 25

APPROPRIATE USE OF THE MODIFIED ALLAN VARIANCE

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Abstract

The Allan and related variances are powerful and useful estimates of stability and are used widely within the scientific community. As with any statistical estimator, however, the Allan variance is not intended for use without first understanding the statistical nature of the data. This paper illustrates cases when the Allan variance reacts differently than one might expect, not due to a flaw in the Allan variance but due instead to underlying properties of the data that dictate the use of an alternative variance estimate.

An analysis of the conditions under which the Modified Allan variance may understate or overstate stability is discussed. For example, when comparing stationary data sets, it is expected that the one with the smaller sample variance would also have the smaller Modified Allan variance. This is not the case for all samples. The relationship between Modified Allan variance and the autocovariance is derived, and the effect of the covariance structure of data on the Modified Allan variance is shown empirically. Specific statistical tests and graphical procedures are recommended in order to aid researchers in determining if the application of the Modified Allan variance to a given data set is appropriate.

Paper 26

UNCERTAINTY OF STABILITY VARIANCES BASED ON FINITE DIFFERENCES

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Abstract

This work presents a unified algorithm for evaluating the measurement uncertainty of a class of stability variances used in the time and frequency field. Since the early 1970s, a number of papers have treated this problem for the Allan, modified Allan, and Hadamard variances. Recognizing that these are special cases of a general form, we have found a consistent approach that works for the whole class in the presence of integer power-law phase noises, from white phase to random run frequency.

Included are stability variances based on mean-square dth differences of phase (unmodified variances) or average phase (modified variances), for d = 1, 2, or 3. (The case d = 1 is included for completeness.) We insist on distinguishing a target variance from its estimators; thus, for each variance we treat two unbiased estimators, called overlapped and nonoverlapped, which shift the differencing filter by the sample period τ_0 and the averaging period τ, respectively. For example, we include the nonoverlapped estimator of modified Allan variance, even though its IEEE standard definition is actually a formula for the overlapped estimator. Not included are trend-removal effects and special long-term stability estimators such as total variance and Thêo1. The phase is modeled as the first difference of a continuous-time pure power-law process; this choice of model automatically restricts the phase bandwidth and lets us treat modified and unmodified variances in the same way. Although the algorithm is divided into cases, all the calculations are based on the same theoretical principles, with no empirical formulas.

For an estimator V of a target variance σ^2, the algorithm calculates the effective degrees of freedom, ν =edf V = $2\sigma 4/$(var V); confidence intervals for σ can be calculated by assuming that (ν/σ^2)V is an χ_v^2 random variable. Emphasis is on efficient numerical evaluation of edf with an error tolerance of a few percent. The paper will give sample plots and tables of test cases.

A portion of this work was performed by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Paper 27

A KALMAN FILTER CLOCK ALGORITHM FOR USE IN THE PRESENCE OF FLICKER FREQUENCY MODULATION NOISE

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Abstract

Recent developments, in particular the use of covariance reduction techniques, have demonstrated the potential advantages of Kalman filter algorithms for combin-ing clock measurements. Using this approach, NPL is developing a new clock algorithm to combine measurements from its three active hydrogen masers and caesium fountain clock.

The Kalman filter algorithm models the clock noise as a linear combination of white frequency modulation, random walk frequency modulation and random run frequency modulation. However, measurements made using NPL's active hydrogen masers have indicated the presence of further noise in the form of flicker frequency modulation (FFM). Therefore, in this paper we extend the above algorithm so as to produce a composite clock that over a wide range of averaging times is near optimal in the presence of the above four noise types. The FFM is modelled approximately by a linear combination of Markov noise processes. Each Markov process is included in the Kalman filter and contributes an additional component to the state vector. Both the validity of the model and the effectiveness of adding these additional components to the state vector are examined.

To apply a Kalman filter clock algorithm to real clock data, it is first necessary to estimate the noise parameters used in the process covariance matrix. An iterative method had been developed previously to resolve the magnitude of noise parameters from a measurement time series. This method is extended and applied to a "three cornered hat" of hydrogen maser measurements to estimate the required noise parameters. The performance of the new algorithm is examined when applied to simulated measurements and also to measurements from NPL's hydrogen masers.

Paper 28

A PAPER CLOCK MODEL FOR CESIUM CLOCK ENSEMBLE OF TI

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Abstract

A paper clock model using limited numbers of atomic clocks and a typical time interval counter was developed. The aim of this work is using a small ensemble of clocks and traditional measurement system to generate a time scale keeps both short-term and long-term accuracy. We assumed that the phase difference between any cesium clock and an idea clock is almost unchanged in several nanoseconds in tens of days if drift removed, so that we can average those residual fluctuations of different clocks, and the result paper clock would be more stable and accurate than any contributing clock. We recorded and compared the 1 PPS difference between 7 HP-5071a high performance cesium clocks over 200 days. The weight of each clock was set to be proportional to inversely exponential with the index of each clock's frequency deviation. We didn't set any upper limit of weight because of the inversely exponential has an upper limit itself. For the result, we found the Allan deviation of this paper clock was about 1.6×10^{-13} (t= 10 minutes), compared with hydrogen maser) and a typical Allan deviation of one single cesium clock was $2.8-3.5 \times 10^{-13}$ in our measurement system.

We also developed a mechanism using this paper clock to lock a hydrogen maser via a micro phase stepper. We compared the 1 PPS phase difference between the paper clock and h-maser, adjust the frequency offset with a fixed amount if the phase of h-maser is advanced or retardative with the paper clock, a primitive result showed the phase difference between adjusted micro phase stepper and paper clock can be kept in 1.5 ns. Using this phase-lock mechanism, we can lock the phase of the result paper clock without any prediction algorithm and difference clock can be synchronized by one time scale. It means that we can generate more than one backup time scale system and don't take care of the phase difference between primary and backup systems.

Paper 29

A NEW REALIZATION OF TERRESTRIAL TIME

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Abstract

Terrestrial Time TT is a time coordinate in a geocentric reference system. It is realized through International Atomic Time TAI, which gets its stability from some 200 atomic clocks worldwide and its accuracy from a small number of primary frequency standards (PFS) which frequency measurements are used to steer the TAI frequency. Because TAI is computed in "real-time" and has operational constraints, it does not provide an optimal realization of TT. The BIPM therefore computes another realization TT(BIPM) in post-processing, which is based on a weighted average of the evaluations of TAI frequency by the PFS.

The procedures to process PFS data have been recently updated and we conse-quently propose an updated computation of TT(BIPM). Different strategies are considered: we take into account the recent availability of a number of new Cs fountain PFS, a revised estimation of the stability of the free atomic time scale EAL on which TAI is based, and a possible correlation between different measurements of the same PFS. The performance of the new realization of TT is discussed and is used to assess the accuracy of recent PFS measurements.

Poster 10

ALGORITHM FOR PROCESSING MULTICHANNEL GPS OBSERVATIONS

LU XiaoChun, Chinese Academy of Sciences and Xi Dian University
WU HaiTao, Chinese Academy of Sciences

Abstract

GPS common-view observation is seriously affected by multi-path effects and atmospheric refraction and other factors in lower-elevation cases. The algorithm of data-process in multi-channel GPS observations is to eliminate the data of the satellite observations below 20 degree elevation. The disadvantage of this algorithm is that the observation data are not utilized sufficiently for high precision time comparison. A new algorithm with weight in accordance to the elevation is introduced. The algorithm may decrease the influence of multi-path effect, on the other hand, it may utilize the data of all observations. The result of the multichannel GPS observations datum from Communications Research Laboratory(CRL) and National Time Service Center(NTSC) shows that more accurate time synchronization may be obtained with the new algorithm.

Poster 11

EXTENDING THE TRACKING SCHEDULE OF A SINGLE CHANNEL GPS TIME RECEIVER

Juan Palacio, Francisco Javier Galindo, and Jose A. Lima

Abstract

ROA has successfully increased the number of tacks per day that a single channel GPS time receiver can perform. As a result the number of common view tracks has been increased in a significant amount.

After implementing this method in remote receivers, ROA has increased the quality of the remote calibrations of frequency standards reducing the obtained uncertainty.

In this paper we describe the procedure we have followed for increasing the number of tracks per day, the analysis of the results obtained in remote calibrations and a comparison with the results of a 'regular' tacking schedule GPS time receiver.

Poster 12

COMPARING IGS-DERIVED TIMING INFORMATION TO OTHER TIME TRANSFER METHODS AT THE U.S. NAVAL OBSERVATORY

H. Chadsey, U.S. Naval Observatory

Abstract

There has been considerable interest in recent years concerning the use of International Geodetic Survey (IGS) RINEX data files to perform time transfer. The U.S. Naval Observatory (USNO) has been taking an active involvement in developing this technology as an alternative time transfer method between its Washington, DC and Colorado Springs, CO offices.

This paper will compare the IGS-derived time solutions to GPS Common View (GPSCV) and Two- Way Satellite Time and Frequency Transfer (TWSTFT). It will also show how the IGS data, when converted to CGGTTS format, can be useful in detecting problems and act as an additional verification time transfer tool when operations appear to be normal.

Poster 13

TIME DOMAIN FREQUENCY STABILITY ESTIMATION BASED ON FFT MEASUREMENTS

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Abstract

The standard characterizations of frequency stability are, in the time domain, the Allan (or two- sample) variance and, in the frequency domain, the spectral density function (SDF). The former is mathematically related to the latter by the conversion between time and frequency domain. In this paper, the bias of the Fast Fourier transform (FFT) spectral estimate with Hanning window is checked and the resulting unbiased spectral estimate could be used to calculate the Allan variance. Both the numerical integral and the curve-fitting methods are presented to estimate the variances. The numerical integral is a straightforward way to use and we can get the integral approximation after eliminating some spike points from SDF, e.g. noise caused by ac power. In addition, a common model for SDF is linear combinations of power law processes, which are distinguished by the integer powers, (α), in their functional dependence on Fourier frequency, f, with the appropriate coefficients, h_α. Fitting a form of the above model using standard regression techniques could estimate these coefficients. Cutler's formula is adopted to calculate the integral approximation using these coefficients. The approximations of variances from these two ways are compared and analyzed. Finally, we discuss the limitations and possible errors from these two methods.

Poster 14

A NEW REALIZATION STRATEGY FOR UTC(PTB)

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Abstract

UTC(PTB) has been realized based on the primary clock CS2 and frequency steering in a phase micro stepper for many years. The CS2 performance is characterized by $\sigma_{\mathrm{y}}(\tau) = 3.6 \times 10^{-12}(\tau/\mathrm{s})^{-1/2})$ for τ up to more than 50 days. The frequency steering was performed in steps of 0.5 ns/d on a monthly basis. PTB operates two geodetic GPS receivers (links to IGS and NIST) and TWSTFT equipment in the KU-band (international links) and X-band (link to USNO). To enable assessment of the instability of those modern time transfer techniques the required time and frequency references were derived from a hydrogen maser. Local measurements had to provide the link between UTC(PTB) and the maser. Different frequency distribution equipment, dividers, and pulse distribution equipment, was incorporated and, in consequence, the quality of the individual links was partially deteriorated by the local environment.

UTC(PTB) is now realized on a hydrogen maser steered in frequency without increasing its frequency instability, tracking on average one of PTB's primary time references. UTC(PTB) signals will serve as the reference for all time transfers in the future.

Based on data collected in the past we tried to design an optimum steering algorithm, including the various possible scenarios. The use of two different hydrogen masers on one side, and CS1, CS2, and the fountain CSF1 on the other side, were analysed in the study. Fictive differences UTC - UTC$_f$(PTB) were calculated for each combination, using different frequency prediction strategies, and these differences were analyzed in terms of $\sigma_x(\tau)$ and the predictability of the time difference up to 45 days.

As to be expected, the best results were obtained using the newest maser (large hydrogen flux, low instability) and CSF1 as a steering reference. We are about to establish the practice of data preparation and application of the UTC(PTB) steering on a weekly basis, based on the CSF1, as a laboratory routine. Alternatively, the CS2 has been used as the reference since August 2003.

Poster 15

APPLICATION OF CONTROL THEORY IN THE FORMATION OF A TIMESCALE

P. A. Koppang, D. G. Johns, and J. G. Skinner
U.S. Naval Observatory

Abstract

A timescale is created that joins the short-term stability of several hydrogen masers with the long-term capabilities of an ensemble of cesium frequency standards. Control theory is utilized in a system design that combines frequency standards with varied properties. The control system removes the rate and drift offsets of the masers with respect to the cesium ensemble while minimally perturbing the maser short-term performance. The system is designed using a delayed-state filter model and pole placement techniques. Results will be given from both simulated and measured data.

Paper 30

HIGH PRECISION COUNTER USING DSP TECHNIQUE

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Abstract

A high precision counter using DSP (digital signal processing) is designed for phase and frequency measurement. We use an analog-to-digital converter (ADC) to sample the signal under test. Once the signal is digitized, DSP will be used to run the phase lock loop (PLL) and obtain the necessary information. In our design, the counter is implemented on the Texas Instrument (TI) TMS329C6201 digital signal processor (DSP). The sample data from the ADC is input to the DSP. Additionally, the frequency, 5 MHz, from the Telecommunication Laboratories (TL) standard is used to be the reference clock of the ADC and the DSP. In the DSP, the phase lock loop is created for tracking the signal under test. In phase lock loop operation, the numerical controlled oscillator (NCO) is designed to generate the sine and cosine functions of the desired replica carrier. The sine and cosine functions can product in-phase (I) and quadra-phase (Q) sampled data. By producing I and Q components to the signal under test, the resultant signal amplitude can be computed from the vector sum of I and Q components and the phase angle with respect to the I-axis can be determined from the arctangent of Q/I. Finally, we can determine the phase time difference between the signal under test and the reference clock from the phase angle. The resolution of the phase time difference can be less than 1×10^{-15} second. We also can obtain the frequency difference between the signal under test and the reference clock from the phase angle, and the accuracy of frequency measurement is less than 1×10^{-14}.

Paper 31

PICOSECOND-ACCURACY DIGITAL-TO-TIME CONVERTER FOR PHASE-INTERPOLATION DDS

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Abstract

Direct Digital Synthesis (DDS) solutions are used in several applications such as multistandard digital television, measurement equipment and finely tunable clock generators. These frequency synthesizers are becoming an alternative to PLL-based circuits also in wireless communication systems that often require high frequency resolution and fast frequency switching at the same time [1-3].

Phase interpolation DDS and Direct Digital Period Synthesis (DDPS) architectures have been developed to improve maximum operating frequency, power consumption and system integrability with respect to traditional DDS structures [4-8]. Complex blocks such as DAC and Look Up Tables (LUT) are eliminated, and a precise digitally controlled delay-generator is used to interpolate the clock period, finely positioning each edge of the output signal in the right time instant. A very high-resolution Digital-to-Time Converter (DTC) has been designed for phase interpolation DDS architectures using a 0.35 μm CMOS technology. The delay generation is made in two steps. The first is responsible for the first 32 interpolation levels and is a classic clock interpolator that consists of a 32-tap serial Delay-Locked Delay-Line (DLL) followed by a 32-to-1 multiplexer. The second stage, the architecture of which is shown in the figure, is a novel fine delay generator, very compact in terms of occupied silicon area. It employs 3 identical new-developed digitally controllable delay cells, in which the current starving control is combined with the shunt-capacitor technique [9]. The new delay-cell design allows to realize further 128 interpolation levels inside each time-bin provided by the first step, fully compensating at the same time environmental conditions changes. A negative feedback loop is provided on the current starving control in order to keep the difference between the maximum and minimum introduced delays, locked to the time reference given by the first step time-bin. The effective delay inserted on the output signal is then selected properly configuring the 128 shunt-capacitor loads by a 7-bit control word. According to post-layout simulations, the global circuit is able to perform a 4096 level interpolation of a 120 MHz clock, generating a delay proportional to a 12-bit digital word with the outstanding resolution of about 2 ps.

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Paper 32

PC-BASED TIME INTERVAL COUNTER CARD WITH 200 PS RESOLUTION

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Abstract

We describe a precise time and frequency counter implemented as a computer card with PCI interface. The time intervals are measured over the range from 0 to 43 s with 200 ps resolution (Least Significant Bit) and random error (sigma value) below 200 ps. The counter utilizes the dual interpolation method and comprises two Vernier delay lines integrated in a single FPGA device manufactured using 0.65 μm CMOS technology. The nonlinearity of the lines is corrected automatically with the use of the correction vectors stored in the EEPROM memory. The built-in calibrator allows for precise calibration of the counter at any time. To improve the thermal stability of the counter an external Delay Locked Loop (DLL) is used. The counter card can be synchronized to an external reference clock (10 MHz) or the internal quartz oscillator can be selected as a frequency reference. The card can be used for precise measurements of time intervals between the clock pulses generated by high stability sources of time reference. The polarity of the pulses, the related threshold levels, and the input impedances can be selected by the software. The counter also provides a means of frequency measurement up to 1.1 GHz.

The counter card occupies a single PCI expansion slot in the PC. The related software creates a user-friendly graphic interface and provides advanced functions for control, diagnostics and statistical processing of the measured data. The software can be modified to match the needs of individual users.

We present the design of the card, the relevant tests results and possible applications.

Paper 33

MASTER CLOCK AND TIME DISTRIBUTION SYSTEM FOR THE NASA DEEP SPACE NETWORK

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Abstract

NASA's Deep Space Network (DSN) consists of more than 20 antennas located at three ground communications facilities globally spaced approximately 120 degrees (Goldstone, CA; Madrid, Spain; Canberra, Australia). Each complex simultaneously operates multiple antennas for communication with NASA's inter-planetary spacecraft, for spacecraft navigation, and to detect microwave radiation from distant deep space radio sources for radio astronomy and long baseline interferometry.

Local generation and distribution of precise time and frequency reference signals comprise an essential component of the infrastructure at each complex. Within each complex synchronized timing references are required by approximately 100 users located at distances up to 30 kilometers from the central control center and station Master Clock. Since the DSN is mission critical and simultaneously tracks several missions the timing system must be available at all times and downtime cannot be afforded. This paper describes a highly modular, hot-swappable, and expandable system design for generation and delivery of highly precise and stable timing signals over fiber optic cables to multiple users spread over several kilometers. Operability issues including the design approach to the operator interface, time setup and recovery, redundancy, fault diagnosis, and maintenance will be presented.

Paper 34

LISA: THE LASER INTERFEROMETER SPACE ANTENNA

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Abstract

The Laser Interferometer Space Antenna (LISA) is a deep-space mission, jointly proposed to the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA), for detecting and studying gravitational radiation in the millihertz frequency band [1].

An overview of this new, exciting, and technologically challenging mission will be presented, giving special emphasis to its frequency and timing requirements.

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Paper 35

THE STATE OF THE ART IN AMATEUR TIMEKEEPING

Tom Van Baak, LeapSecond.com

Abstract

One might assume precise time metrology is the exclusive domain of national scientific laboratories, military infrastructure, or professional calibration centers. But there are a number of amateurs who in recent years have built home timing labs purely as a hobby: the performance of which now rival that of some national labs. A even larger number of individuals, perhaps hundreds, own atomic standards and use them to satisfy or fuel their curiosity about the world of ultra precise timekeeping.

The following paper describes an extreme case of one private home timing lab. First, its motivation and history: from a pair of wrist watches 30 years ago, accurate to seconds per week, to a pair of active hydrogen masers today, stable to parts in ten to the 15th. Second, its accomplishments: in the form of web-published experiments, including stability analysis of TCXO and OCXO, comparison of frequency quadruplers, stability comparison of twelve GPS disciplined oscillators, probing the cesium hyperfine clock transition, hydrogen maser auto-tuning results, GPS performance with and without selective availability, homemade software tools for stability analysis, and PC-based instrumentation systems.

Finally, the paper describes the technical challenges that a private home timing lab faces, many of which are the same challenges as a national timing laboratory, though on a smaller scale. Solutions to such problems as budget, power, temperature, space, redundancy, time transfer, security, computer logging and networking, and automated operation are discussed.

Paper 36

THE ROLE OF PRECISE GPS TIME IN MILITARY MISSIONS

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Department of Defense

Abstract

GPS is truly a unique program within the DoD. There is no other DoD-funded and managed program with a user base that is 90% civilian, a large percentage of which are foreign. As demonstrated conclusively in Iraq, military force enhancement value inherent in GPS's highly accurate positioning and navigation signals cannot be overstated. GPS has been effectively embedded in platforms and weapons including "smart" bombs and missiles as well as handheld devices.

Today, the worldwide marketplace for GPS products and services totals some $12 billion annually and is growing at a 20-25% annual rate. GPS remains the world's first and only global, three sdimensional radionavigation system providing continuous operational PNT service. Freely available to all and providing nano-second timing accuracy, it is the most powerful positioning, navigation, timing and synchronization technology ever fielded.

Although GPS is generally recognized as a source of highly accurate positioning information, its importance as a timing system is not as well appreciated. The fundamental building block upon which GPS is based is very accurate time. If GPS were to experience widespread failure or disruption, the impact to military users as well as the civil community could be devastating. Loss of GPS timing would severely hamper military operations, disable police, fire, and ambulance communications around the world; disrupt the global banking, equity markets, and financial systems, which depend almost exclusively today on GPS timing to synchronize connectivity; and interrupt the operation of our transportation and electric power distribution systems.

This paper explores some of the applications of and the growing dependency on precise GPS time in a myriad of military missions. It also examines how future military uses of GPS are expected to be effected as a result of the ongoing GPS modernization activities.

Paper 37

GLOBAL POSITIONING SYSTEM(GPS) – MODERNIZATION PROGRAM STATUS AND IMPLICATIONS FOR THE PTTI USER

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U.S. Air Force
Donald Latterman, Science Applications International Corporation

Abstract

Objective: The objective of this paper is to continue to keep users of Global Positioning System (GPS) precise time transfer aware of the changes planned for the GPS to provide a more robust precise positioning and timing service to both its military and civil users. The GPS is undergoing Modernization to provide more robust signal service to the civil user and more secure service to the military user.

Results: This paper provides a brief overview of the system status today and then discusses national-level policy direction and reasons to modernize the GPS signal architecture to meet future user requirements. It discusses how and when the GPS Modernization program will provide more GPS capability for the military and civil users in the near-term. It summarizes the plans to implement new signal services by modifying the Block IIR and Block IIF space vehicles, upgrading the Operational Control Segment (OCS) and changing military GPS User Equipment (UE.) Next, it explains the GPS-III program objectives and its approach to defining both military and civilian user needs for precise positioning and timing services over the next 30 years and designing the system architectures that will meet these requirements. The paper addresses what these changes mean to the GPS timing user, including identifying requirements, benefits, and impacts on user equipment, including GPS timing receivers. It discusses how both military and civil GPS timing users can get involved in the requirements process in order to influence system changes. The paper concludes by highlighting the challenges faced by the GPS Joint Program Office (JPO) that is responsible for taking these changing requirements and turning them into a precise positioning and timing service capability for both civil and military users. It presents some of issues that need to be addressed from an international perspective, including spectrum allocation / usage and compatibility with Galileo, as to where these issues are today and where they need to go in the future.

Conclusions: Most precise time / time interval users realize that the Global Positioning System (GPS) provides precise coordinated time and very accurate time transfer. However, most users are not fully aware of the complexity of the system that provides this basic utility, nor are they exposed to the technical and managerial challenges in planning, designing, developing, maintaining and changing it. In order to provide a more precise and robust positioning and timing service to meet the future needs of both its military and civilian users, the GPS Joint Program Office (JPO) started a comprehensive program to modernize the GPS signal architecture. The precise time users of GPS need to stay informed of changes planned for this system to ensure their future needs are met for precise time and highly accurate time transfer.

Significance: Users of GPS precise time transfer and relative time need to be aware of the system changes that will influence future equipment designs (as GPS timing receivers) and service capability (continuity of service, robustness). The Annual Meeting is a very effective means of informing the PTTI community on what is planned for GPS and the timeframe the service changes will be available.

Paper 38

DISTRIBUTED COHERENT RF OPERATIONS

John A. Kosinski, U.S. Army

Abstract

Among the contributing factors to transformation of the U.S. military are information operations (IO) and network-centric warfare (NCW). IO gives emphasis to the criticality of information in conflict: there is obvious advantage to knowing the enemy's capabilities, disposition, and intentions while denying him any such knowledge of your own forces. IO may be either offensive or defensive in nature, and includes aspects such as electronics support (ES, intelligence gathering and threat warning) and electronic attack (EA, jamming, spoofing, deception). NCW gives emphasis to the synergistic operation of multiple entities distributed across the battle-space. In NCW, the whole is much greater than the sum of the parts. Here we consider potential NCW approaches to IO in the context of RF signals, which leads to the concept of Distributed Coherent RF Operations.

Two scenarios are immediately of interest. The first scenario considers a network of low-cost (preferably expendable) RF receivers distributed across the battle-space. The goal of such a network is to provide pervasive and persistent SIGINT and ES coverage of the battle-space. The challenge is to do so in a dense RF environment against multiple simultaneous RF signals and in the presence of multi-path and co-channel interference. Beam-forming and multi-channel signal processing can mitigate these effects provided that that multiple channels of RF data are acquired and processed coherently. While coherent multi-channel ES systems already exist, they are not distributed systems, and they are substantially more expensive per channel than allowable for an expendable system. The objectives and requirements for this scenario will be discussed.

The second scenario considers a similar network of transmitters undertaking the EA mission with greater sophistication than simple noise jamming. Here, the objective is to use a number of low power transmitters with precise accounting for propagation delays, carrier phase alignment, and center frequency in order to yield coherent jamming at a specific location on the battlefield with minimal disruption elsewhere. The objectives and requirements for this scenario also will be discussed.

Paper 39

FLEET USE OF PRECISE TIME

Thomas Myers, CFFC

Abstract

This paper provides a perspective on current use of precise time and future requirements for precise time as they relate to individual shipboard systems, networks, satellite system, and clocks.

It is based on studies performed by PMW 156 and others and upon recent demonstration of of the use of two way satellite time transfer (TWSTT) on USS Mount Whitney. Data will be provided to show what kind of precise time standards and policies are in use today and how new timing architectures will provide cost effective improvements in support of FORCEnet and other Navy and DoD initiatives that will require precise timing.

Paper 40

ONE-LITER ION CLOCK: NEW CAPABILITY FOR SPACEFLIGHT APPLICATIONS

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Abstract

We describe progress toward the development of a small Hg+ Ion clock suitable for space-based applications. The goal is an ultra-high stability clock in a volume of only 1-2 liters. We have designed and fabricated a prototype small physics package and have measured signal-to-noise and line-Q showing $10^{-13}\tau^{-1/2}$ short-term performance, well matched to space-qualified USO performance at 1 second. This exceptionally good short- term stability in a small clock, equals that of the larger clocks recently developed (even Cs fountains) and follows from improvements in optical design.

The architecture for this small clock relies on ion shuttling between a quadrupole and multi-pole rf trap, similar to the much larger ground-based clocks. Two such clocks, developed and tested at JPL, showed excellent stability of 5×10^{-16} at $\sim$ 1 day averaging. One of these clocks was subsequently delivered to the USNO where long-term stability as good as $2 - 3 \times 10^{-16}$ was measured with respect to their best clock ensemble.

This paper will review the physics package details, show measured clock resonances and discuss some of the challenges remaining in reaching flight-worthiness in the 1-2 liter package.

Paper 41

INVESTIGATIONS OF THE RUBIDIUM CLOCK'S MULTI-MONTH EQUILIBRATION FOLLOWING INITIAL ACTIVATION

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Abstract

Over the past several years, anecdotal evidence has grown suggesting that rubidium gas-cell frequency standards exhibit a long "equilibration" period of somewhere between 30 and 70 days following their initial activation. The mechanism driving this equilibration is not well understood, and has been the subject of debate. Generally, the lamp intensity has also been observed to undergo a slow variation following the clock's turn-on, and since the clock's resonant frequency depends on light intensity via the light-shift effect, there has been speculation regarding the light-shift as a possible mechanism for long-term equilibration. However, helium permeation has also been suggested as a contributing mechanism. Since the gas cells are manufactured free of He, over time, He from the atmosphere will permeate into the cell changing the cell pressure, and thus the resonant frequency.

In order to characterize the nature and discern the mechanism of equilibration in Rb clocks, we have initiated a long-term (many months) study of Rb clocks from different manufacturers. (Presently, we have four clocks from two different manufacturers; additional clocks will be incorporated into the study in the future.) We continuously monitor the Rb clocks' frequency relative to a cesium clock (referenced to GPS), the lamp intensity, crystal control voltage, loop-lock indicator, and clock temperature. For all clocks, we find a long-term equilibration of clock frequency and lamp intensity with a time-constant of multiple weeks. This observation, consistent with previous findings, suggests that the long-term equilibration process is a generic feature for this type of atomic frequency standard. However, though the data indicates that a clock's frequency and lamp's intensity slowly change in a correlated fashion, the data are ambiguous regarding a causal relation between long-term lamp intensity change and clock frequency change. Potential mechanisms for the frequency equilibration process will be presented along with results of additional experiments and simulations to test the plausibility of various mechanisms. Specifically, we hypothesize that an underlying equilibration mechanism (perhaps associated with helium permeation or alkali redistribution in both the resonance cell and lamp) may be the root cause of the lamp's and the clock frequency's slow equilibration.

Paper 42

END RESONANCES FOR ATOMIC CLOCKS

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Abstract

Gas-cell Rb clocks have traditionally used the 00 resonance between the sublevels of azimuthal quantum number mF = 0 in the hyperfine multiplets with total angular momentum F = I $\pm$ 1/2. The main advantage of the 00 resonance is the weak, quadratic dependence of the frequency on the ambient magnetic field. However, at the high temperatures and Rb densities needed to compensate for shorter path lengths in miniature cells, spin-exchange collisions between Rb atoms broaden the 00 resonance and decrease its amplitude. Further losses in resonance amplitude occur because the small cells require a high buffer-gas pressure to hinder the diffusion of Rb atoms to the cell walls. At buffer-gas pressures above a few hundred torr, collision broadening of the optical absorption line makes it difficult for frequency-selected pumping light to produce a population difference between the initial and final states of the 00 resonance. These disadvantages can be overcome by using "end resonances," corresponding to transitions from the "end sublevels" of maximum or minimum azimuthal angular momentum. Pumping with circularly polarized D1 light causes most of the atoms to accumulate in the end sublevels, and this leads to unusually strong amplitudes for the end resonances, even at buffer-gas pressures of several atmospheres. The high spin polarizations reduce the resonance line broadening due to spin exchange collisions. In this paper, we discuss recent experimental and theoretical work on the physics of end resonances in Rb vapor. We show quantitatively how the resonance amplitudes and widths depend on the cell dimensions and temperature, on the buffer-gas pressure, on the pumping-light intensity, and on spatial gradients of the temperature and magnetic field. We present data demonstrating the superior signal-to-noise ratios and narrower linewidths of the end resonances, compared to the 00 resonance. The magnetic- field dependence of end resonance frequency can be dealt with by simultaneously using the microwave and Zeeman end resonances, originating from the same end sublevel, in feedback loops to lock the magnetic field and the clock frequency. The advantages of end resonances over 00 resonances would be even greater for Cs than for Rb.

Paper 43

USING LASER DIODE INSTABILITIES FOR CHIP-SCALE STABLE FREQUENCY REFERENCES

T. B. Simpson and F. Doft, Jaycor/Titan
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Abstract

Semiconductor Lasers are known to undergo significant changes in their output characteristics when subjected to external optical perturbations such as near-resonant injection from an external source or optical feedback. Over a range of operating conditions the perturbations can induce a periodic pulsating output where the pulsation frequency can be controlled by the bias point of the laser(s), and amplitude (and frequency offset) of the injection. The output optical spectrum can be adjusted to be dominated by two strong frequency components with a controllable offset. Adding a weak microwave modulation to the bias can lock the pulsation frequency to this reference. Such a spectrum is nearly ideal for the excitation of Coherent Population Trapping (CPT) resonances of gas-phase atomic media such as Cesium (Cs) and Rubidium. We describe the double locking of a laser diode to the CPT optical (852 nm) and microwave (9.2 GHz) resonances in Cs gas in a cell containing Cs and a buffer gas. The microwave power required for the modulation reference is a small fraction of the dc-bias power, unlike a directly modulated laser diode. The combination of all- optical excitation of the Cs gas and reduced microwave electronics specifications is very useful for the fabrication of ultra-small frequency references.

Paper 44

THE CHIP-SCALE ATOMIC CLOCK RECENT DEVELOPMENT PROGRESS

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Abstract

We have undertaken a development effort to produce a prototype chip-scale atomic clock (CSAC). The design goals include short-term stability, $\sigma_y(\tau = 1\ \text{hr}) < 1 \times 10^{-10}$, with a total power consumption of less than 30 mW and overall device volume $< 1\ \text{cm}^3$. The stringent power requirement dominates the physics package architecture, necessarily dictating a small ($< 1\ \text{mm}^3$) volume gaseous atomic ensemble interrogated by a low-power semiconductor laser. At PTTI 2002, we reported on initial experimental investigations leading to the decision to develop an architecture based on the coherent- population-trapping (CPT) interrogation technique.

In this paper, we will report on the engineering progress that has been accomplished on the CSAC development effort over the past year, including the development of mission-specific vertical-cavity surface emitting laser sources (VCSELs) and techniques for manufacturing miniature ($<1\ \text{mm}^3$) cesium vapor cells comprised of anodically-bonded silicon and glass, utilizing semiconductor processing techniques.

We have developed VCSELs at two different wavelengths, 852 nm and 894 nm, permitting CPT interrogation of either of the cesium "D2" or "D1" resonance features. Measurements of the signal contrast and linewidth of the two resonance features will be compared and frequency stability measurements of the CSAC brassboard prototype will be presented.

This work is supported by the Defense Advanced Research Products Agency, Contract # NBCHC020050.

Paper 45

PRELIMINARY RESULTS ON CHIP-SCALE RUBIDIUM ATOMIC CLOCK

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Tom McCleland, Frequency Electronics Incorporated
Al Pisano, University of California, Berkely

Abstract

Our industrial and academic collaborative group is developing technology to enable a 30-milliWatt chip-scale atomic clock system. Our technology development includes photon generation assisted by integrated radioactive sources, novel methods for realizing inexpensive Rb resonance cells, and nano-mechanical resonators for magnetic tuning of cells. In this paper we present preliminary results obtained in realizing these technologies. Photon generation using radioactive thin films of nickel-63 inside micromachined cells with integrated magnets will be presented. Interaction of emitted electrons, and ionization processes inside the cavity are modeled in the presence of magnetic fields using plasma and ionization physics. This model demonstrates that plasmas could be excited at lower power to maintain photon output lowering the power budget of the atomic clock. Secondly we will report on measurement of linewidths from micromachined resonance cells and glass-capillaries (1 kHz measured with 1 mm ID cell). Novel techniques for sealing Rb vapor in a micromachined chamber coated with line-width improving wax will be presented. Anodic bonding of glass to bulk-etched micromachined silicon cavities are filled and sealed in-situ using existing bulb-making facilities at FEI. The resonance testing of these cells is underway and will be presented by the time of the conference. Nanomechanical resonators to be used for magnetic regulation of the atomic resonance will be presented with models for nanoscale magnetic actuators based on thin-film piezoelectric materials. The above technologies will be shown to eventually realize a low-power chip-scale atomic clock.

Paper 46

MINIATURE PHOTONIC CLOCK BASED ON RB VAPOR

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Abstract

The opto-electronic oscillator (OEO) [1] is a generic architecture based on direct conversion of light energy into spectrally pure microwave signals. The stability, and accuracy of this device is determined by that of the energy storage element in the feedback loop, which in the most conventional configuration, is a fiber delay line. Replacing the delay of the fiber with an atomic cell can lead to transfer of the stability and accuracy of the atomic resonance to the OEO. With this configuration, an atomic clock with a self-contained, high performance local oscillator is realized. In this paper we will describe such a device in detail, and discuss ways to architect it in a miniature package. The key to the reduction of the size of the atomic vapor based OEO is in the use of a resonant lithium niobate modulator based on high Q whispering gallery modes. Such a microresonator has been demonstrated at JPL [2], and can function both as the microwave filter and the modulator. The efficiency of the modulator is also an important factor that allows operation with small (a few mW) of microwave drive power.

[1] Steve Yao and Lute Maleki, "Optoelectronic microwave oscillator," Journal of Optical Society of America-B, 13, 1725 (1996).

[2] V. S. Ilchenko, A. A. Savchenkov, A. B. Matsko, and L. Maleki, "Sub-Micro Watt Photonic Microwave Receiver," Photonics Technology Letters, 14, 1602 (2002).